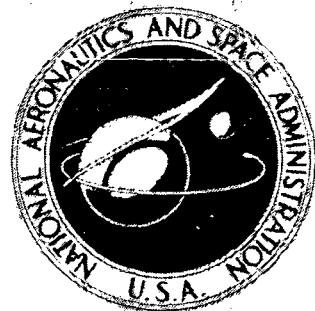


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EFFECT OF PRESSURE ON
TANGENTIAL-INJECTION FILM COOLING
IN A COMBUSTOR EXHAUST STREAM

by Cecil J. Marek

Lewis Research Center
Cleveland, Ohio 44135

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EFFECT OF PRESSURE ON TANGENTIAL-INJECTION FILM COOLING IN A COMBUSTOR EXHAUST STREAM

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SUMMARY

A tangential-injection film-cooled test section was placed in the exhaust stream of a high-pressure combustor. The combustor was a rectangular-segment combustor used for research on the effect of pressure and fuel atomization on combustor exhaust emissions. The combustor exhaust stream conditions varied from pressures of 1 to 20 atmospheres, temperatures of 600 to 1500 K, and Mach numbers of 0.14 to 0.47. The fuel-air ratio of the combustor ranged from 0 to 0.02. Film-cooling data were taken with ambient-temperature cooling air at axial distances less than 16 slot heights from the slot exit. The test section was 4.0 centimeters long, and the film-cooling slot exit was 0.254 centimeters high.

The film-cooling effectiveness was found to be independent of pressure over the range of conditions tested. The data were correlated by a turbulent-mixing film-cooling correlation, and a turbulent-mixing coefficient of $0.05+0.02$ was determined.

INTRODUCTION

This investigation evaluates the effect of pressure on the film-cooling effectiveness. Extensive film-cooling data exist in the literature which were obtained at atmospheric pressure. With increases in compressor-pressure ratio in advanced gas turbines, the need exists to extrapolate the film-cooling data to higher pressures. Arguments may be made that either the effectiveness of the cooling film may decrease with increasing pressure or the effectiveness may not change with changes in pressure. As the pressure is increased, the Reynolds numbers of both the hot-gas stream and the film-cooling stream increase for fixed velocities. The film-cooling effectiveness may decrease with increasing pressure because increasing Reynolds numbers may increase the mixing between the hot-gas stream and the film-cooling stream and thereby cause a decrease in the film-cooling effectiveness. Also, as the

Reynolds number increases, the hot-gas boundary-layer thickness upstream of the slot exit decreases, thus increasing the momentum of the hot-gas stream close to the wall.

Reference 1 states that within a combustor where the hot-gas turbulence is high, the film-cooling effectiveness is controlled by the hot-gas turbulence level. The turbulence level as inferred from the turbulent mixing coefficient remained constant over a wide range of Reynolds numbers, indicating that the film-cooling effectiveness is not a large function of Reynolds number. It may then be concluded that the film-cooling effectiveness should not change significantly with pressure. However, all of the data in reference 1 were taken at near 1 atmosphere pressure. Each of these arguments may be valid in a different range of operating conditions.

In order to determine the effect of pressure on the film-cooling effectiveness in a combustor environment and to determine whether data taken at 1 atmosphere could be extrapolated to higher pressures, a tangential-injection film-cooled test section was placed in the exhaust stream of an experimental gas-turbine combustor, and data were taken at pressures of 1, 10, and 20 atmospheres. Other combustor exhaust conditions ranged from temperatures of 600 to 1500 K, fuel-air ratios from 0 to 0.02, and Mach numbers from 0.14 to 0.47. The test section was placed in the free jet issuing from the combustor in order to provide an environment where hot-gas temperature and velocity measurements could be obtained for use in determining the film-cooling effectiveness. The test section was 4.0 centimeters, and the film-cooling slot exit was 0.254 centimeter high. The film-cooling air was at ambient temperature.

The film-cooling effectiveness data at the three pressure levels are compared to the turbulent-mixing correlation developed in reference 1. The effect of pressure on the value of the turbulent-mixing coefficient was determined.

APPARATUS AND INSTRUMENTATION

Test Combustor

A tangential-injection film-cooled test section was placed in the exhaust stream of a high-pressure combustor. The combustor was a rectangular segment producing a hot-gas jet 4.8 centimeters high by 30 centimeters wide. A schematic of the combustor with the location of the film-cooled test section is shown in figure 1.

A complete description of the combustor, fuel injectors, and associated equip-

ment is given in reference 2. The combustor was fired with ASTM-A1 fuel introduced through air-atomizing fuel injectors. Midway through the test program, the fuel injectors were changed from radial jets to splash cones. A detailed description of both of these injectors is given in reference 2. This change did not affect the heat-transfer environment in the exhaust stream.

The combustor operated efficiently over a wide range of pressures and fuel-air ratios. The pattern factor δ of the exhaust stream, defined as

$$\delta = \frac{\frac{T_{\text{maximum}} - T_{\text{average}}}{T_{\text{exhaust}} - T_{\text{exhaust}}}}{\frac{T_{\text{average}} - T_{\text{combustor}}}{T_{\text{exhaust}} - T_{\text{inlet}}}} \quad (1)$$

ranged from 0.45 to 1.15. These values of the pattern factor are much higher than would be desired for a gas-turbine combustor and produced some large temperature gradients in the exhaust stream. The hot-gas temperature profile was measured with a five-point aspirating platinum/platinum-13-percent-rhodium thermocouple rake which traversed the exhaust stream and stopped every 1.27 centimeters. The total temperature used in the film-cooling study was determined by averaging the five readings on the rake at the single position directly in front of the film-cooled test section. Temperature differences as high as ± 200 K existed at this position at a pattern factor of 0.5 and a hot-gas temperature of 1300 K.

Test Section

Film-cooling air and slave-cooling air were introduced independently to the test section. The film-cooling air cooled the test surface. The slave-cooling air first flowed concentrically with the film-air inlet tube to maintain the film-air at ambient temperature, and then it cooled the undersurface of the test section. The film-cooling air was injected parallel to the combustor exhaust stream through a continuous slot. The cooling-air flow rates were measured with venturi meters. Figure 2 is a sketch of the test section. An air gap between the test surface and the inlet-stream manifold minimized convection cooling. At the end of the test surface, the air gap was blocked with insulation to prevent hot-gas convection on the rear side.

The test section was constructed of 0.16-centimeter-thick, type-316 stainless steel. The test surface was 4.05 centimeters wide by 4.0 centimeters long. The film-cooling slot exit was 0.254 centimeter high. Two identical test sections were

used in the series of experiments. The first test section was damaged midway through the program. Check points taken with the second test section agreed with previous results taken with the first test section.

Six Chromel-Alumel thermocouples were spot welded on the bottom of the test surface within the air gap at the locations shown in figure 2. The thermocouples were located along the centerline of the test surface. At a location 2.54 centimeters downstream of the slot exit, two additional thermocouples were placed radially to indicate the lateral thermal gradients developed. One of the three thermocouples at the 2.54-centimeter location failed early in the program, and only two thermocouples are reported at this location. The inlet-film temperature was measured upstream of the test section. Since the cooling-air system consisted of concentric tubes with slave air in the outer tube, the film air was maintained at ambient temperature until exiting from the slot. The inlet-film temperature was determined by extrapolating the test surface temperatures to the slot exit, as well as from initial measurements before inlet thermocouple failure. On the second test section, no inlet thermocouple was installed because of the good agreement between the inlet thermocouple and the upstream thermocouple as obtained with the first test section.

The test section was placed so that the test surface was not directly exposed to radiation from the combustor. A photograph showing the location of the test section and traversing hot-gas rake in the exhaust section is shown in figure 3.

RESULTS AND DISCUSSION

Experimental film-cooling data are presented at pressures of 1, 10, and 20 atmospheres. The 1-atmosphere data were taken under altitude blowout conditions. The 10-atmosphere data represent the cruise condition; and the 20-atmosphere data represent the sea-level takeoff pressure for an advanced gas-turbine combustor. A list of other combustor operating variables at these conditions is given in table I. A list of the experimental film-cooling data is given in table II.

The wall temperatures were converted to the film-cooling effectiveness by assuming that the film temperature is equal to the wall temperature. Calculations showed that this assumption caused a maximum error of 10 percent in the film-cooling effectiveness. The film-cooling effectiveness η_f may be related to the downstream distance parameter x/M_s by the following expression which was developed in reference 1:

$$\eta_f \equiv \frac{T_h - T_f}{T_h - T_c} = \frac{1}{1 + C_m \frac{x}{Ms}} \quad (2)$$

where T_h is the hot-gas temperature, T_f is the film temperature at a given distance x from the film-cooling slot exit, T_c is the inlet-film-air temperature, and C_m is the turbulent-mixing coefficient. In the parameter x/Ms , s is the slot height, and M is the mass-flux ratio of the cooling air to the hot-gas stream, $\rho_c U_c / \rho_h U_h$ (ρ is density and U is velocity). The cooling-air mass flux $\rho_c U_c$ was determined from the cooling-air mass flow rate and the exit slot area of 1.03 square centimeters.

The hot-gas mass flux $\rho_h U_h$ was computed by dividing the combustor mass flow rate by the combustor exhaust area. The combustor exhaust area, which was 4.8 centimeters high by 30 centimeters wide, was used in the calculation because it was assumed that the flow separated at the combustor exhaust and produced a hot jet, and it was assumed that jet expansion, contraction, or deflection was negligible in the 10 centimeters between the combustor exhaust and the test section (see fig. 1). If any change of the hot-gas jet occurred, it was assumed to be similar at all the operating pressures tested. No correction was made for the effect of the cooler side walls because, although the gas density was higher, the hot-gas velocity was lower than the mean, which indicated a nearly constant mass flux throughout the hot-gas stream.

The experimental data are shown in figure 4 along with the turbulent-mixing film-cooling correlation (eq. (2)) for various values of C_m . It is seen that over the pressure range studied, there is no significant change in the turbulent-mixing coefficient C_m for the tangential-film-injection configuration studied. More data had been taken at other intermediate pressures. The data at the other pressures showed no significant deviation from the 1-, 10-, and 20-atmosphere data.

The value of C_m in the combustor exhaust stream is 0.05 ± 0.02 . This value is considerably lower than the value of 0.15 obtained at atmospheric pressure within a different combustor designated as a "one-side-entry" combustor (ref. 1). But the value of 0.05 is above the value of 0.01 found in low-turbulence wind tunnels. The mixing seems to be dominated by the turbulence level of the hot-gas stream, which seems to be more a function of combustor geometry than the Reynolds number of the hot-gas stream. The data scatter are assumed to be caused by the uncertainty in the

hot-gas temperature, as indicated by the large pattern factor of the combustor exhaust stream. Temperature differences as large as 200 K existed in the combustor exhaust stream at a pattern factor of 0.5 and an average exhaust temperature of 1300 K. Four other methods of averaging the hot-gas thermocouples to compute the hot-gas temperature were investigated to try to reduce the scatter in the data. Two of the methods were (1) using only the centerline thermocouple, and (2) averaging the center three thermocouples at the three rake positions upstream of the test surface. The scatter was not reduced by changing the method of averaging used to determine the hot-gas temperature.

In order to evaluate the effects of radiation and axial wall conduction, the test-surface temperatures, including these effects, were computed with the use of a constant value of 0.05 for the turbulent-mixing coefficient C_m . The gas emissivity was computed with the use of the nonluminous flame correlation of Reeves (ref. 3). The predicted wall temperatures are plotted against the experimental temperature in figure 5. Most of the predicted data are within 25 percent of the experimental values. The error is defined as the deviation between the predicted and experimental wall temperatures over the difference between the experimental wall temperature and the inlet-cooling-air temperature. Since the predicted data do not show either a positive or negative systematic trend from the experimental data at the three pressure levels, accounting for radiation and axial-wall conduction would not change the conclusions already reached. The data indicate that assuming a constant value of the turbulent-mixing coefficient does result in good correlation of the data over the large pressure range of from 1 to 20 atmospheres. Small changes in the effectiveness may exist with pressure, but because of the scatter in the data, these changes are not discernible. Most of the scatter is presumed to be caused by uncertainties in the hot-gas temperature.

The effect of pressure is important when computing combustor-liner temperatures. Norgren (ref. 4) has shown that the combustor-liner temperature within the primary zone does increase with pressure at a fixed reference velocity because the soot concentration within the primary zone increases significantly, which increases the contribution of the radiation flux to the liner. When convection cooling is present, the balance between the various modes of cooling changes with pressure. In this report it has been shown that the film-cooling effectiveness will remain constant with

changes in pressure for a given geometry and a given value of the downstream distance parameter, x/M_s .

In this experiment, only tangential film injection was used, and it would not be safe to conclude that there is no pressure effect for the case where the film-cooling stream has a normal component of velocity.

SUMMARY OF RESULTS

Film-cooling data were obtained over a pressure range of 1 to 20 atmospheres. The test section was located in the exhaust stream of a high-pressure combustor. There was no significant change in the film-cooling effectiveness with pressure for tangential film injection. The turbulent-mixing correlation worked well over the complete pressure range with the assumed constant value of the turbulent-mixing coefficient C_m of 0.05 ± 0.02 .

Lewis Research Center,

National Aeronautics and Space Administration,

Cleveland, Ohio, April 4, 1973,

501-24.

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3. Reeves, D.: Flame Radiation in an Industrial Gas Turbine Combustion Chamber. Rep. NGTE Memo. M.285, National Gas Turbine Establishment, Oct. 1956.
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TABLE I. - COMBUSTOR OPERATING CONDITIONS

Test condition	Combustor air flow, kg/sec	Inlet temperature, K	Pressure, atm	Fuel-air ratios	Reference ^a velocity, m/sec
Blowout	0.73 and higher	480	1 or /and lower until blowout	0.02	22.5 and higher
Idle	3.38	425	4	.007	22.5
Cruise	6.06	589	10	0 to 0.02	22.5
Takeoff	12.12	589 and 755	20	0 to 0.02	22.5 and 27.7

^aBased on maximum combustor cross sectional area of 467 cm².

TABLE II. - EXPERIMENTAL DATA

Run	Pressure, atm	Mass flow rate of hot gas, kg/sec	Hot-gas temperature, T_h , K	Fuel-air ratio	Pattern factor, δ	Smoke number (a)	Film air flow rate, kg/sec	Mass flux ratio, M	Inlet cooling air temperature, T_c , K	Wall temperature T_f at specified distance x downstream, K		
										$x = 0.64$ cm	$x = 1.59$ cm	$x = 2.54$ cm
1	10.20	6.074	582	0	0	--	0.0526	1.21	371	390	427	459
2	9.50	5.938	605	0	0	--	.0490	1.14	353	365	405	451
3	9.60	5.874	1392	b,.0160	.65	10	.0939	2.21	378	429	486	603
4	9.60	6.033	1392	b,.0160	.65	10	.1025	2.42	377	427	476	618
5	9.60	5.974	1392	b,.0160	.65	10	.0562	1.32	375	474	562	730
6	9.60	5.987	1392	b,.0160	.65	10	.0295	.70	369	522	616	789
7	8.77	5.833	1273	b,.0157	.65	25	.1061	2.52	377	420	464	576
8	8.77	5.915	1273	b,.0157	.65	25	.0549	1.30	375	459	544	705
9	8.77	5.933	1273	b,.0157	.65	25	.0275	.65	373	582	663	834
10	9.46	5.978	1167	b,.0155	.65	35	.1107	2.56	377	408	445	538
11	9.46	5.883	1167	b,.0155	.65	35	.0535	1.25	375	437	501	626
12	9.46	5.842	1167	b,.0155	.65	35	.0336	.77	370	485	551	672
13	9.46	5.910	1167	b,.0155	.65	35	.0376	.87	362	453	527	635
14	18.78	12.215	1249	b,.0132	1.15	58	.1093	1.24	382	454	513	664
15	18.78	12.229	1249	b,.0132	1.15	58	.0531	.60	380	559	626	793
16	18.78	12.211	1249	b,.0132	1.15	58	.0567	.64	378	534	607	767
17	18.67	12.242	914	b,.0067	.62	39	.1083	1.22	382	431	472	563
18	18.67	12.229	914	b,.0067	.62	39	.0531	.60	381	486	520	616
19	18.79	12.170	1511	b,.0165	.62	35	.0821	.93	380	511	595	762
20	18.79	12.170	1511	b,.0165	.62	35	.1002	1.14	381	481	557	727
21	18.79	12.174	1511	b,.0165	.62	35	.0531	.60	379	611	715	915
22	9.63	6.368	1125	.0120	.56	18	.1406	3.06	378	411	453	549
23	9.63	6.296	1125	.0120	.56	18	.0535	1.17	374	447	511	621
24	9.63	6.364	1125	.0120	.56	18	.0290	.64	369	537	680	770
25	9.69	6.400	1340	.0163	.76	19	.0540	1.17	371	472	548	557
26	9.69	6.341	1340	.0163	.76	19	.0299	.64	369	587	767	---
27	19.45	12.433	1001	.0085	.45	13	.0490	.54	371	479	555	---
28	19.45	12.324	1001	.0085	.45	13	.1016	1.13	376	431	475	---
29	19.45	12.365	1001	.0085	.45	13	.0966	1.08	378	436	480	---
30	19.43	12.174	1177	.0135	.62	19	.0939	1.07	379	467	518	---
31	19.43	12.329	1177	.0135	.62	19	.0534	.61	377	523	638	---
32	19.43	12.261	1177	.0135	.62	19	.1103	1.25	379	451	511	---
33	19.43	12.242	1294	.0165	.70	28	.1002	1.13	380	474	542	---
34	19.46	12.360	1294	.0165	.70	28	.0522	.59	378	556	697	---
35	19.76	12.610	935	.0095	.64	--	.1315	1.44	381	426	474	---
36	19.84	12.619	1023	.0095	.54	35	.1320	1.44	380	433	482	---
37	1.21	1.374	948	.0105	.59	--	.01501	1.51	295	366	401	475
38	1.21	1.379	948	.0105	.59	--	.00826	.83	295	393	434	493
39	1.21	1.393	948	.0105	.59	--	.00943	.95	295	396	437	515
40	1.21	1.393	948	.0105	.59	--	.00386	.39	293	544	638	668
41	1.18	1.538	1224	.0181	.62	--	.01429	1.29	295	413	458	578
42	1.18	1.524	1224	.0181	.62	--	.00821	.74	295	471	541	656
43	1.18	1.533	1224	.0181	.62	--	.00490	.44	294	608	724	802
44	1.09	1.424	1187	.0193	.65	--	.01442	1.40	296	403	445	.558
45	1.09	1.415	1187	.0193	.65	--	.00816	.79	296	456	515	620
46	1.09	1.393	1187	.0193	.65	--	.00476	.46	295	579	673	754
47	.98	1.388	1094	.0199	.71	--	.01470	1.46	296	379	419	511
48	.98	1.370	1094	.0199	.71	--	.00789	.78	296	428	480	574
49	.98	1.402	1094	.0199	.71	--	.00481	.48	296	529	606	681
50	9.84	6.491	569	0	0	--	.0073	.15	318	469	509	528
51	9.84	6.504	569	0	0	--	.0267	.57	335	384	413	466

^aMeasured in the exhaust stream according to SAE 1179 methods (see ref. 2).^bCalculated from the average temperature rise at the combustor.

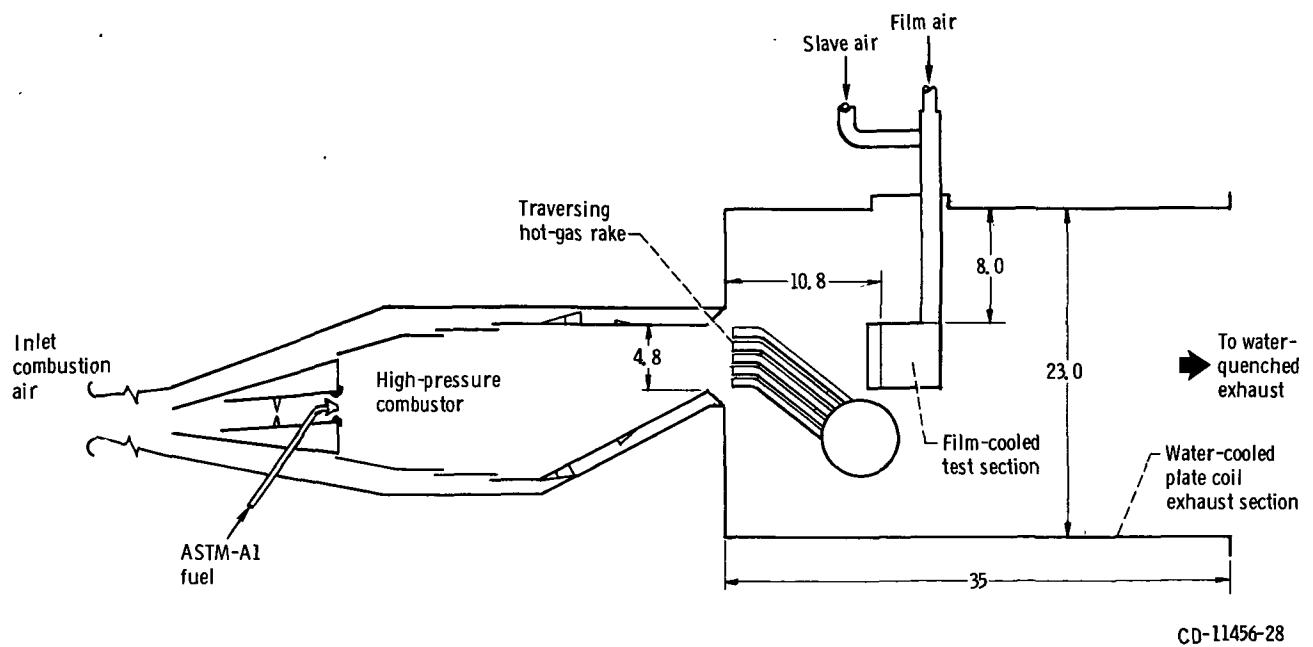


Figure 1. - Schematic of high-pressure combustor and exhaust section showing the location of the film-cooled section.
Dimensions are in centimeters.

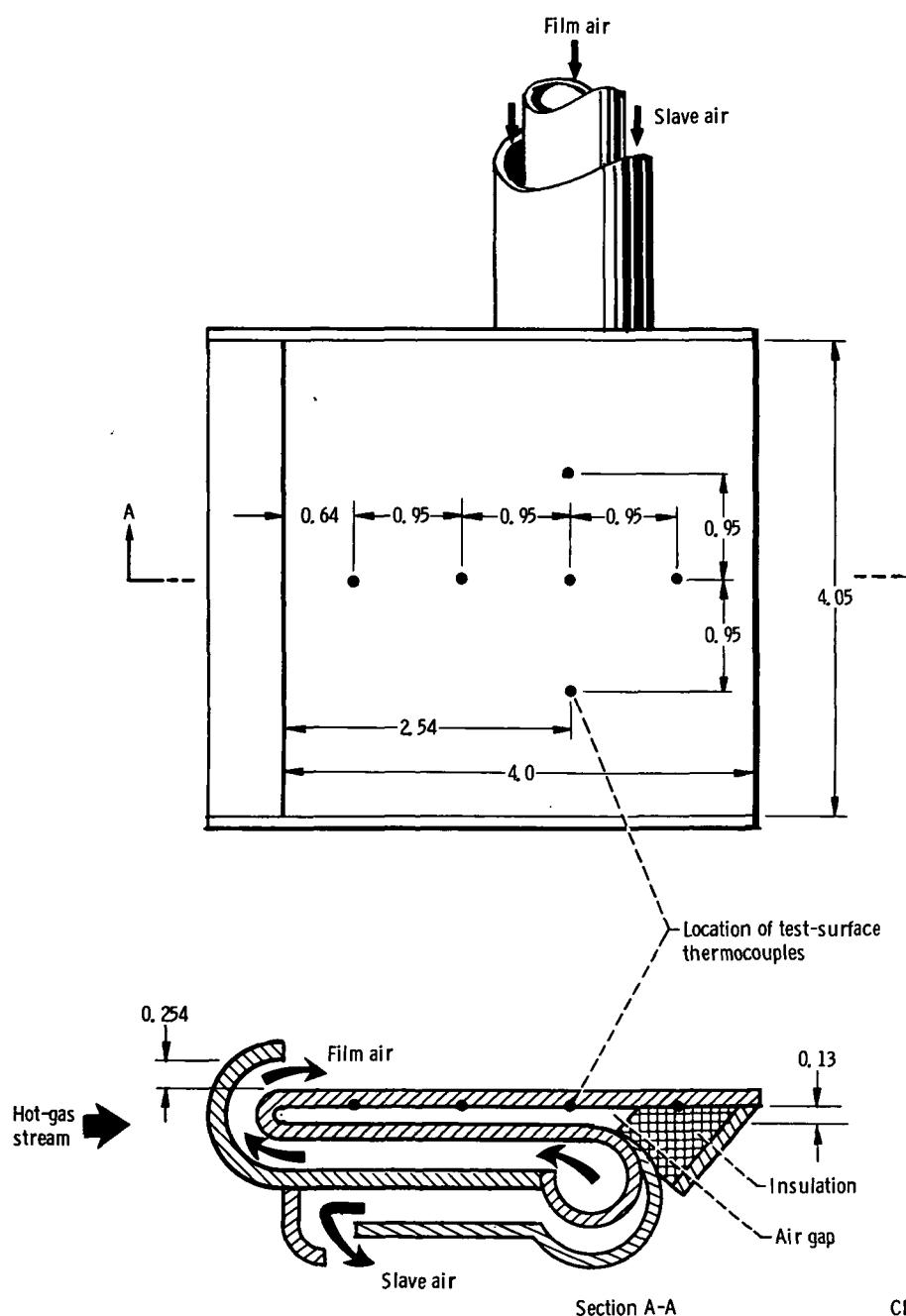


Figure 2. - Sketch of film-cooled test section showing location of wall thermocouples. Dimensions are in centimeters.

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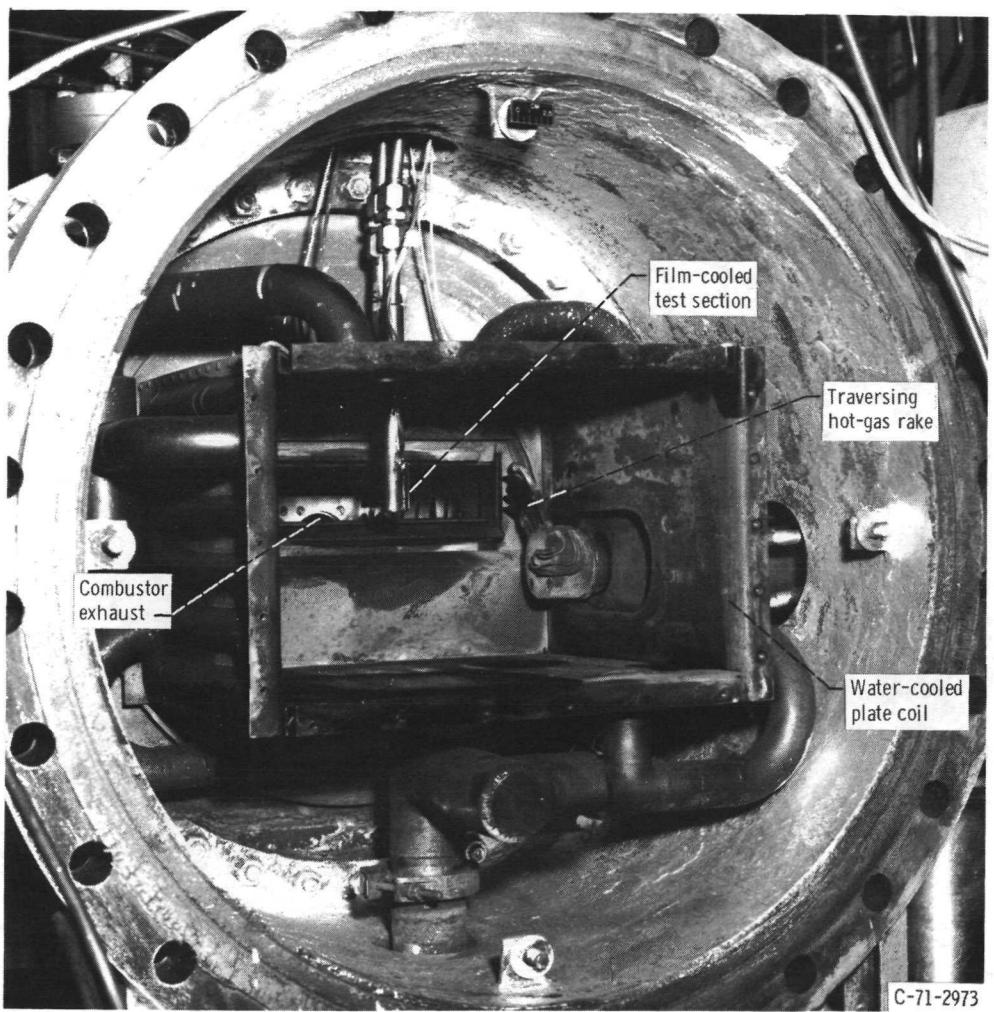


Figure 3. - View looking upstream in combustor exhaust showing location of film-cooled test section and traversing rake.

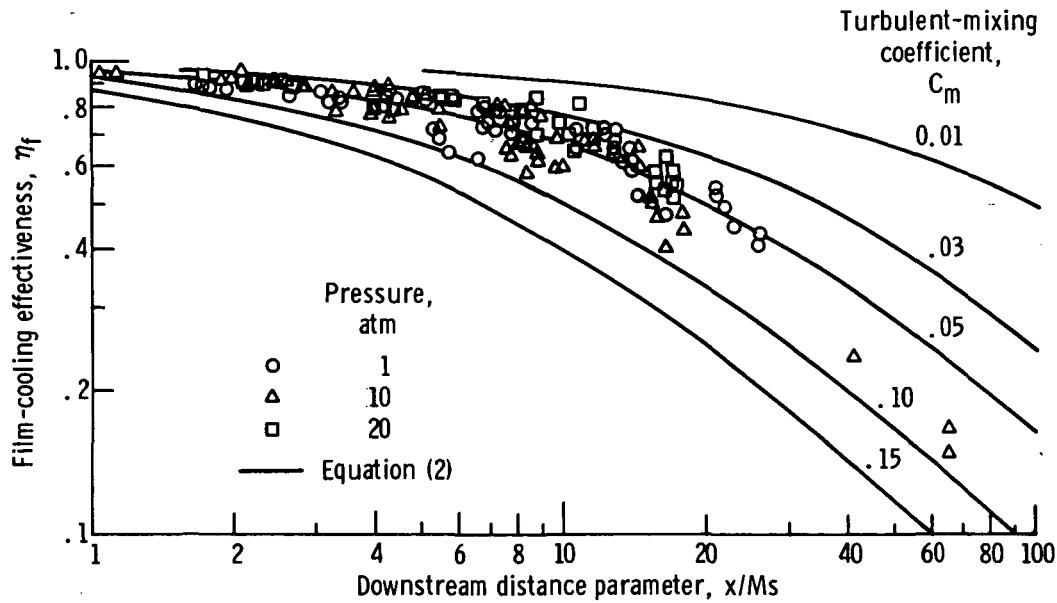


Figure 4. - Effect of pressure on turbulent-mixing film cooling correlation.

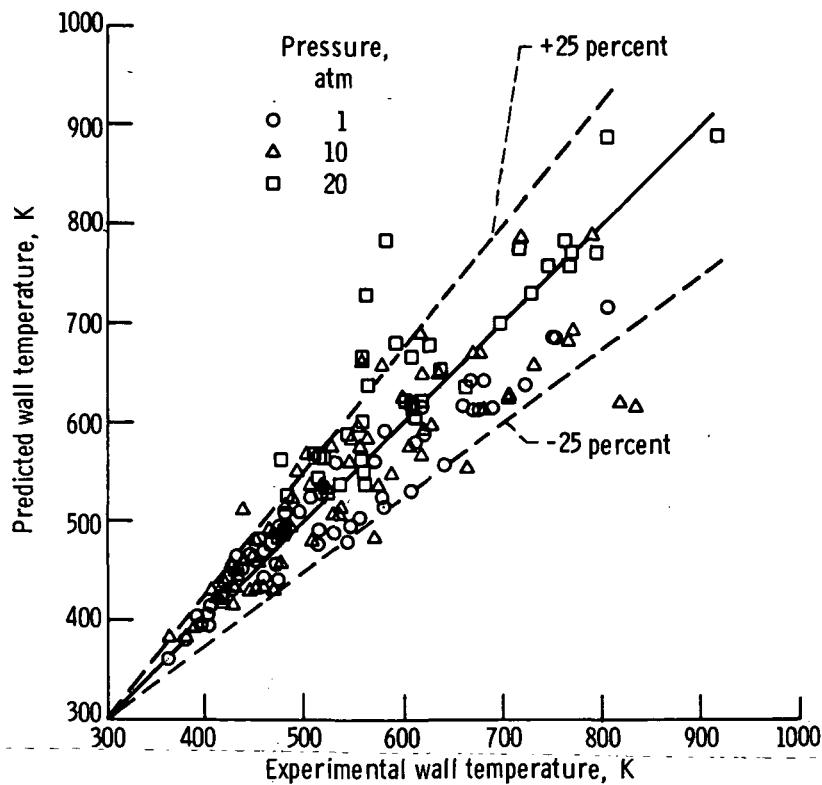


Figure 5. - Comparison of experimental wall temperatures with predicted values at pressures of 1, 10, and 20 atmospheres.

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